R&D on supercritical CO_2 and krypton as natural refrigerants for the thermal management of future detectors and electronics

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TRACEABILITY	
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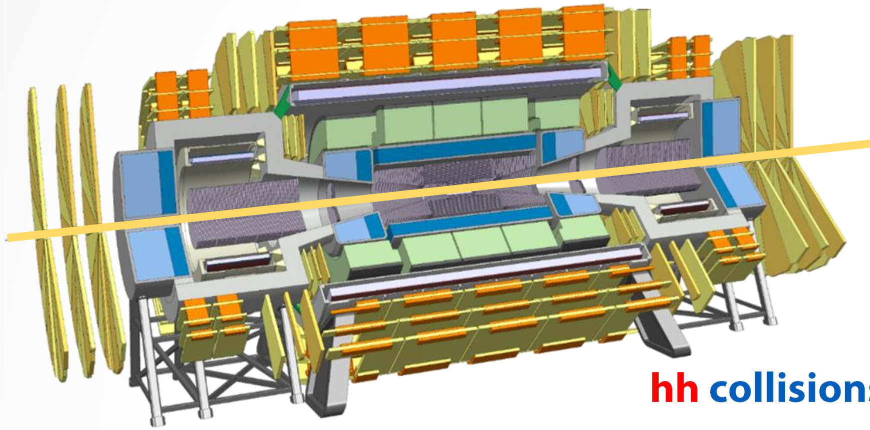
Introduction to CERN/EP-DT-DC

- The CERN EP-DT-DC section (*Detector Technology-Detector Cooling*) has the mandate of developing high performance light weight cooling solutions for particle detectors.
- Founded in 2008 as a project, it started to develop CO_2 based cooling solutions for the Phase-1 upgrade of CMS (operational 2015) and later ATLAS (operational 2014).
- EP-DT-DC also introduced the micro-channel cooling (cooling embedded in silicon), see details of the technology in talk on Thursday 14:45
- EP-DT-DC developed the full-scale CO_2 cooling systems for the phase 2 upgrade of ATLAS and CMS (1-2 orders of magnitude scaling up in power)
  - Currently being build, first systems running
  - Ful implementation in LS3
- EP-DT-DC is now starting to look in the future cooling needs
  - Going colder for higher radiation environments (LHC-HL, FCC pp)
  - Improve efficiency for warm cooling applications (FCC-ee)
  - Ultra low temperature cooling for Silicon Photo Multiplier (SiPM)
- EP-DT-DC is available to give support for your cooling challenges

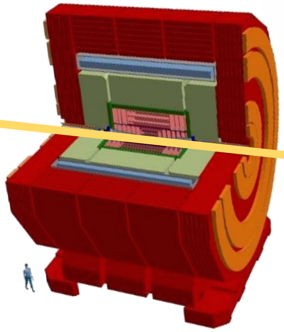
Which direction do we go for cooling in the future for silicon detectors?

FCChh, HE-LHC, …



hh collisions

CLIC, FCCee, ILC, CEPC,…



e^+e^- collisions

- *High radiation dose (~ 100 MGy/10years)*
  - *Very high integrated dissipated power*

- *Unprecedented spatial resolution (1-5 µm point resolution)*
- *Low dissipated power (<50mW/cm^2)*

CO2, Kr

Evaporative cooling
Super critical cooling

Also an option for SiPM cooling

Very Low Temperature, High Pressure

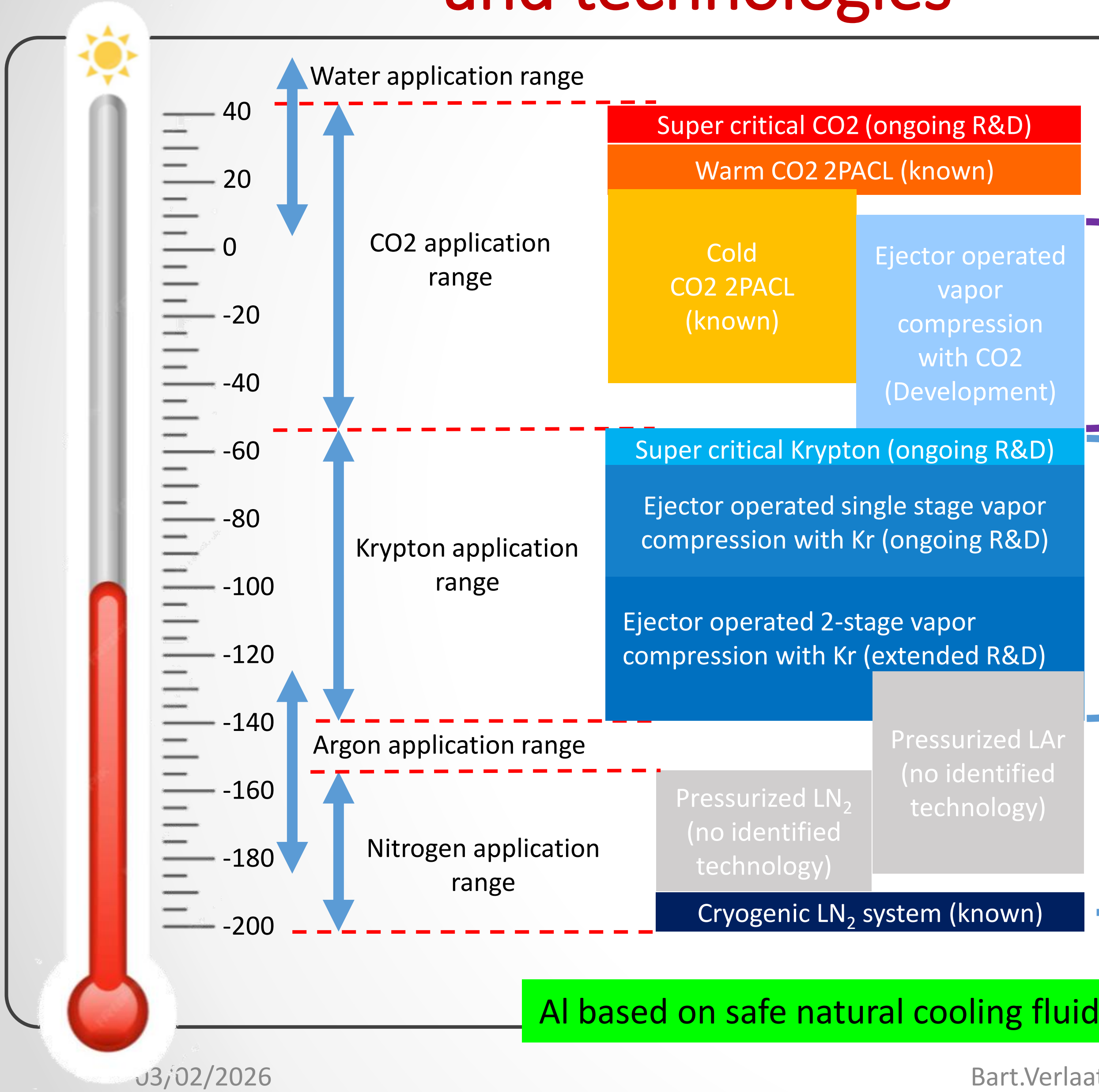
Direct Air cooling
Liquid cooling
Super critical cooling
Evaporative cooling

CO2, Water, air

Room Temperature, Minimum Material budget

We only focus on natural cooling fluids

Identified detector cooling fluid choices and technologies



Current R&D in DRD8-WG3
EP-DT-DC & Offenburg (Germany)

The 2PACL technology with CO2 has many applications within HEP.
CERN/EP-DT-DC is the center of expertise

Development of an oil free CO_2 compressor needed

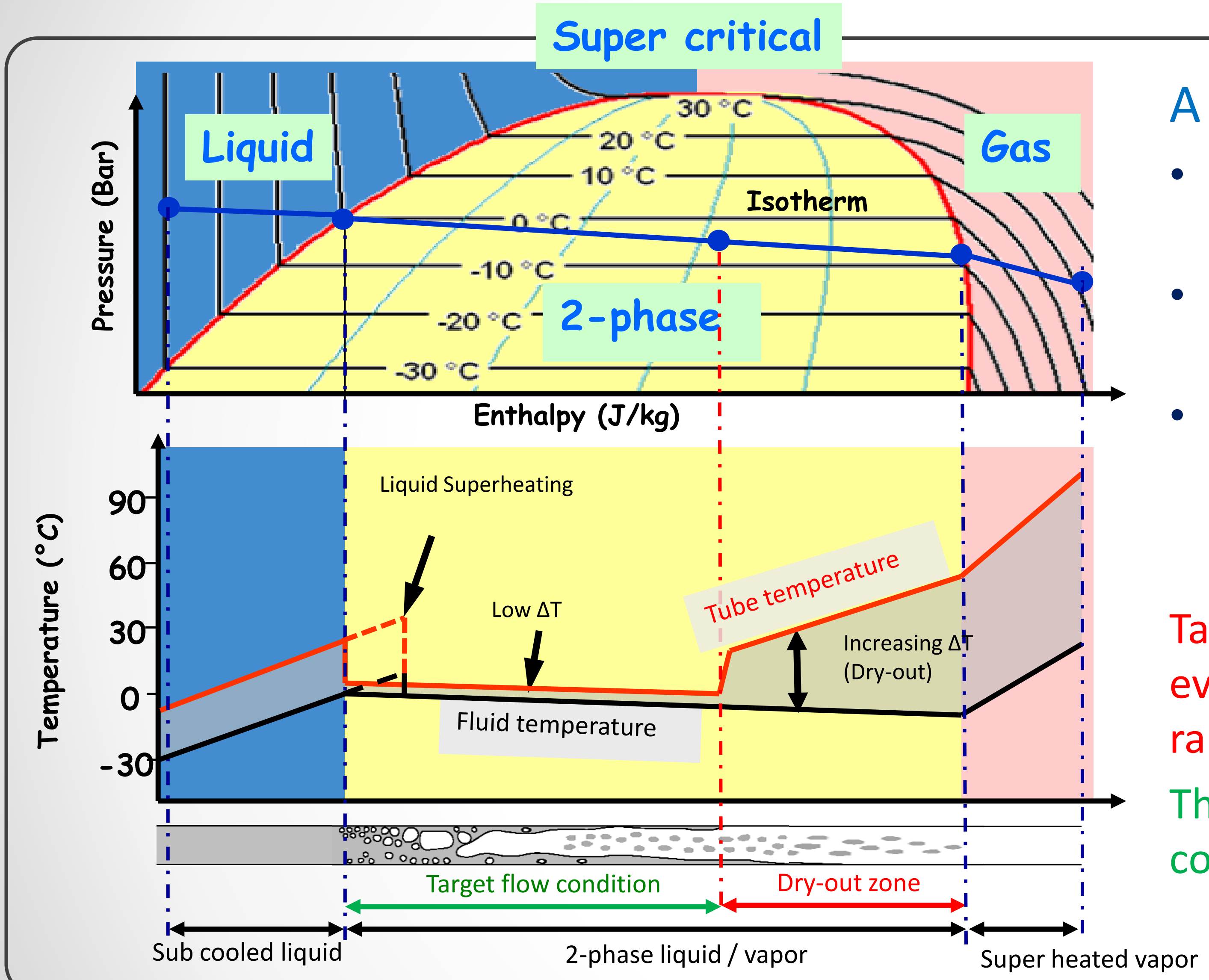
Lots of similarities, likely be similar technology, even interchangeable

Current R&D in DRD8-WG3
EP-DT-DC & NTNU (Norway)

Low pressure LN_2 technology has many applications within cryogenics CERN/Cryolab is the center of expertise

AI based on safe natural cooling fluids only for a green and safe detector future

Cooling pipe behavior explained



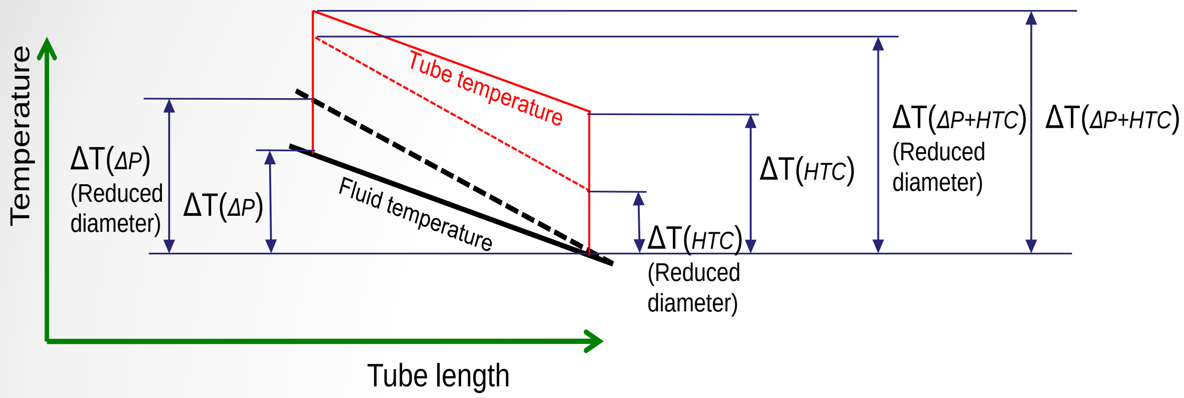
A cooling pipe with heat load:

- Increasing temperature in single phase (liquid, gas and supercritical)
- Decreasing temperature in 2-phase due to pressure drop
- Best heat transfer in 2-phase at the lower vapor quality range

Target area for detector cooling is 2-phase evaporative cooling in the lower vapor quality range

This gives the lowest gradients and lowest cooling mass

Optimization of the heat transfer to the cooling fluid



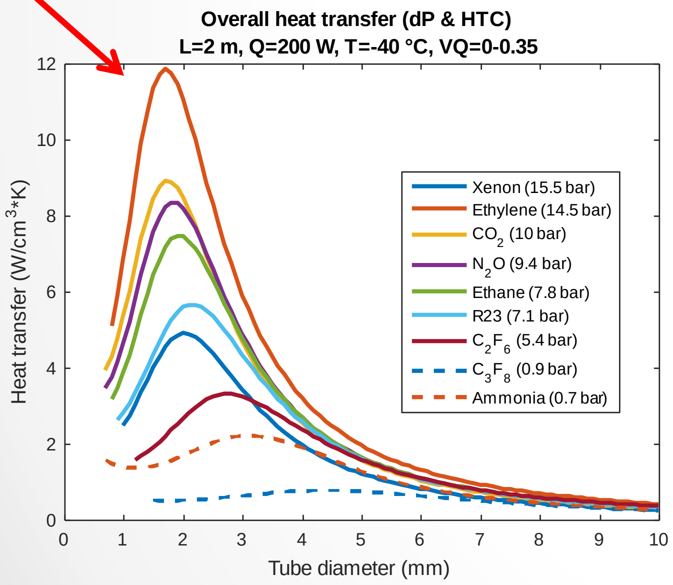
The overall performance is the sum of the pressure drop losses and the heat transfer losses

Overall Volumetric Heat Transfer Conduction VHTC (W/m³K):

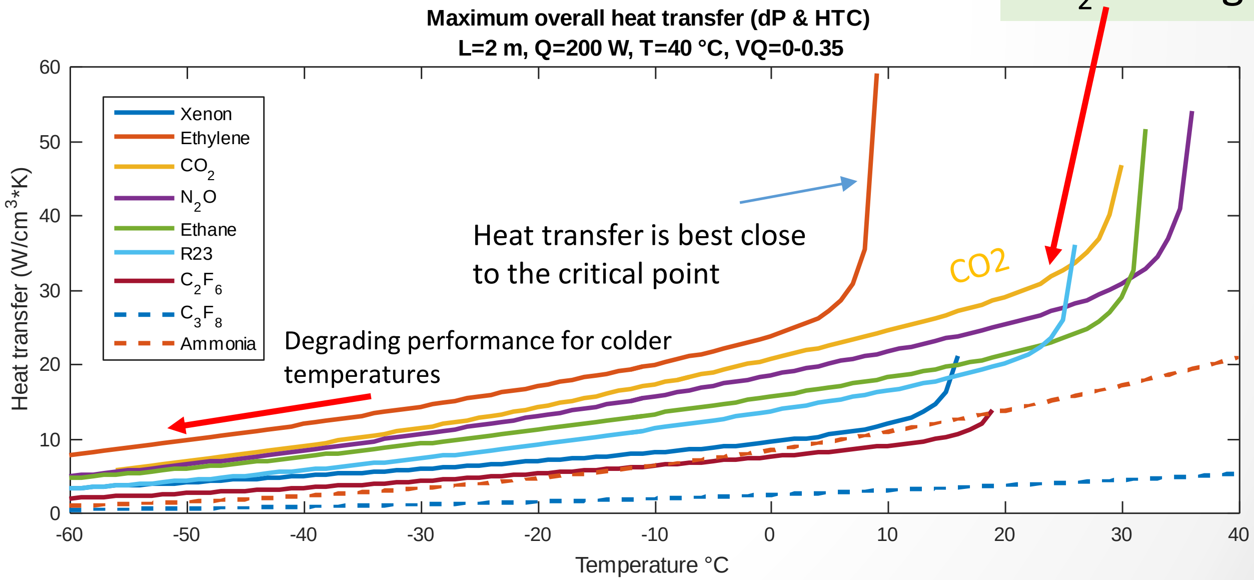
$$\frac{Q}{V_{tube} * \Delta T(\Delta P + HTC)}$$

Why we developed CO_2 cooling

Optimum



The performance is the best at high temperatures

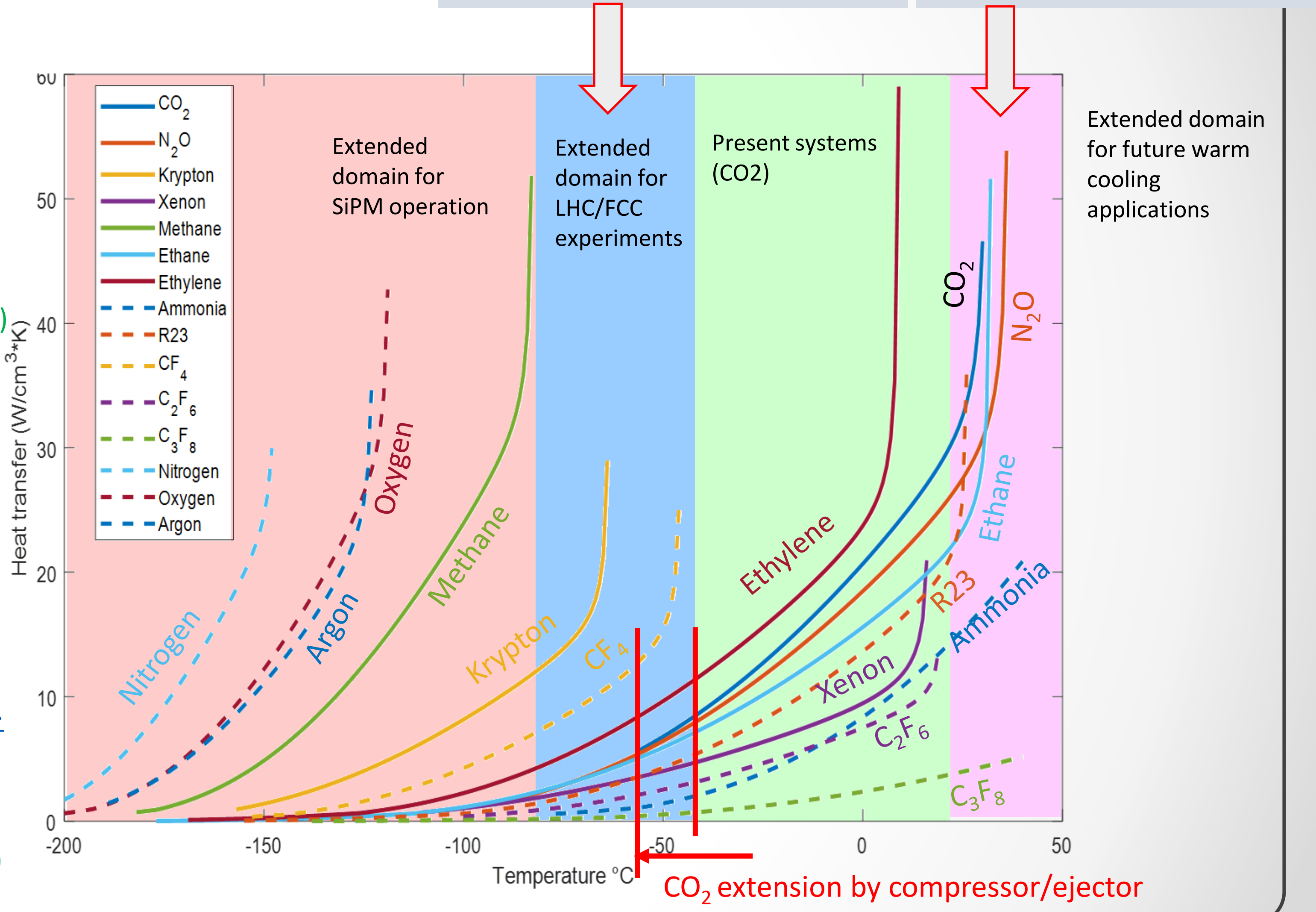


Future cooling domains

Sub & Supercritical Krypton cooling, PhD project by **Luca Contiero** and **Lukas Köster** (CERN/NTNU)

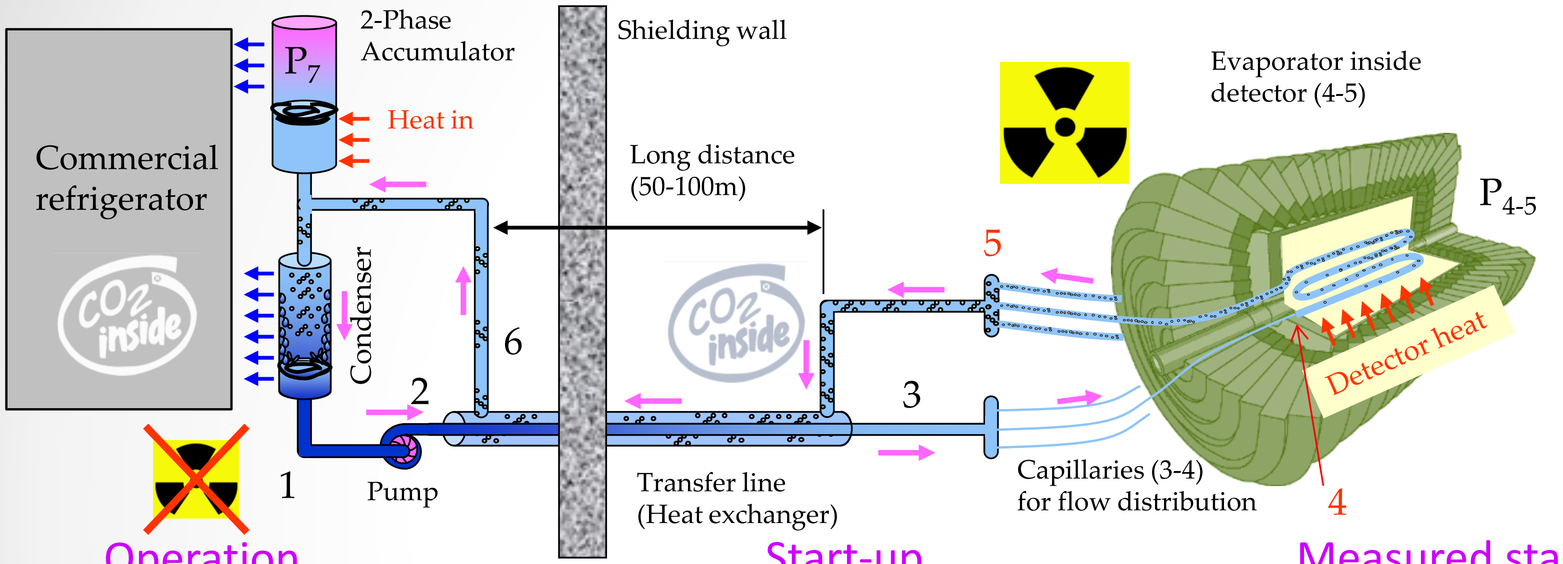
Sub & Supercritical CO2 cooling, PhD project by **Camila Pedano** (CERN/KIT/HSO)

- New cooling research topics beyond the capacity of CO_2 2PACL (25/-40°) have been identified for future detectors using the same volumetric heat transfer approach
  - Warm detectors for future eē accelerators (>20°C)
    - Super and sub critical CO_2 (EP-DT-DC)
  - Colder CO_2 close to triple point
    - New cycle with oil free compressor and ejector
  - Extended cold detectors for LHC upgrade or FCC-pp (<-60°C)
    - Super and sub critical Krypton (EP-DT-DC)
  - Silicon PM detectors (-200 / -80°C)
    - Liquid or gaseous Nitrogen (Cryolab)
    - 2-stage Krypton > -140°C , (EP-DT-DC)
- The future research perspectives are defined in the following research programs
  - DRD8-WG3
    - Forum on Tracking Detector Mechanics 2025 (16-20 June 2025): Overview · Indico,
    - 2nd DRD8 Collaboration Meeting (October 14, 2025) · Indico
  - ECFA R&D roadmap https://cds.cern.ch/record/2784893.
  - WP4 of the CERN EP R&D on Experimental Technologies (https://ep-dep.web.cern.ch/rd-experimental-technologies)

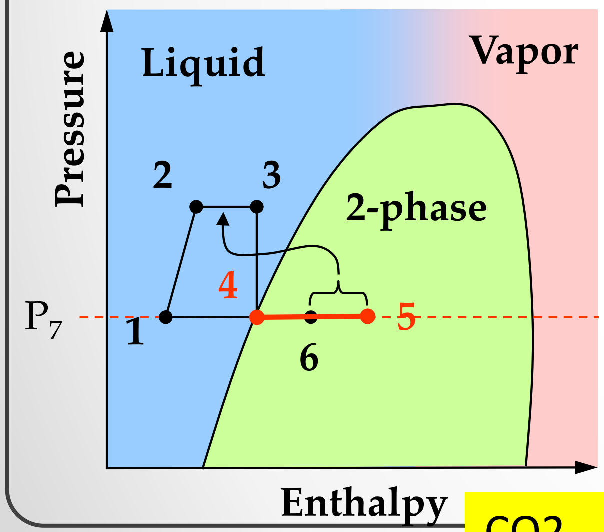


CO_2 2PACL: The current default technology for detector cooling from +25 °C to -40°C

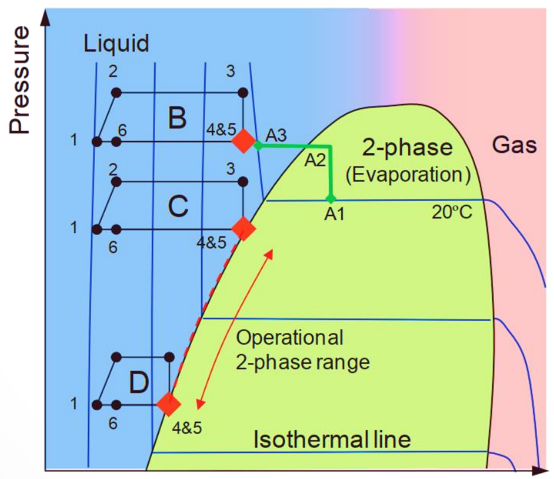
(2-Phase Accumulator Controlled Loop)



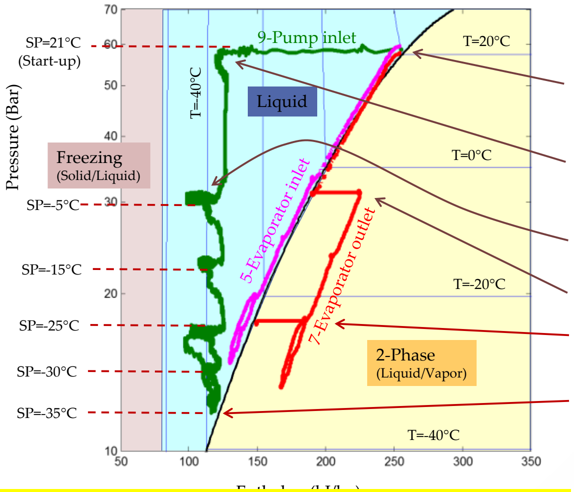
Operation



Start-up



Measured start-up



- Low vapor quality cooling for best heat transfer in small tubes
- Large operational temperature range
  - +25°C / -40°C on detector
  - Independent to applied heat load
- Liquid loop start-up
  - No thermal shocks
- Very stable evaporator temperature control at a distance
  - Pdetector (P4-5) ≈ Paccumulator (P7)
- Accurate controlled cooling down speed
  - Typical >1°C/min
- All active control in distant plant in an accessible area

CO2 - 2PACL has become the detector cooling standard in HEP

- Reliable, Stable & Easy to operate down to -40°C on detector

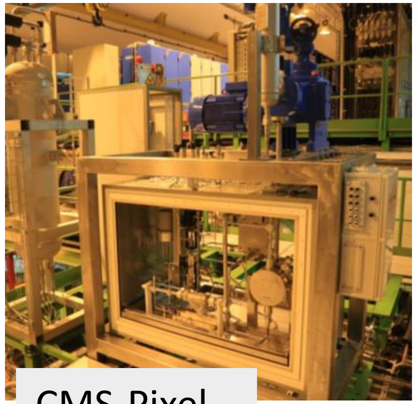
EP-DT
Detector Technologies

CO_2 2PACL cooling systems at CERN

AMS@ISS
2011-
Birth of 2PACL

LHCb-Velo
2008-2018
Birth of CO2 cooling

ATLAS-IBL
2014-



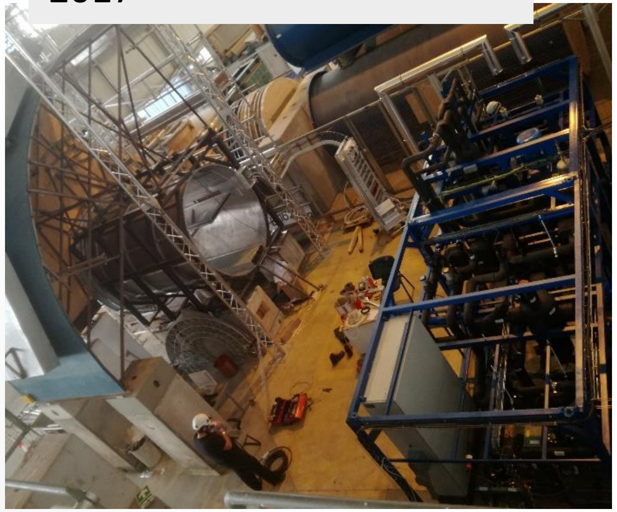
CMS-Pixel
2015-

Traci and Lucasz lab coolers

DEMO 2PACL
2022-2024

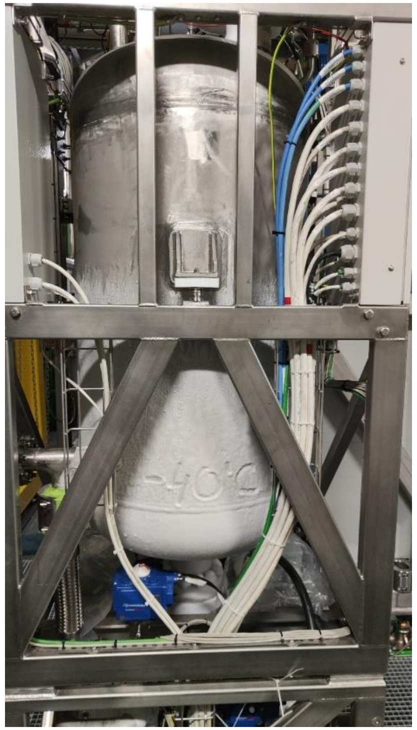
LHCb-Mauve
2019-

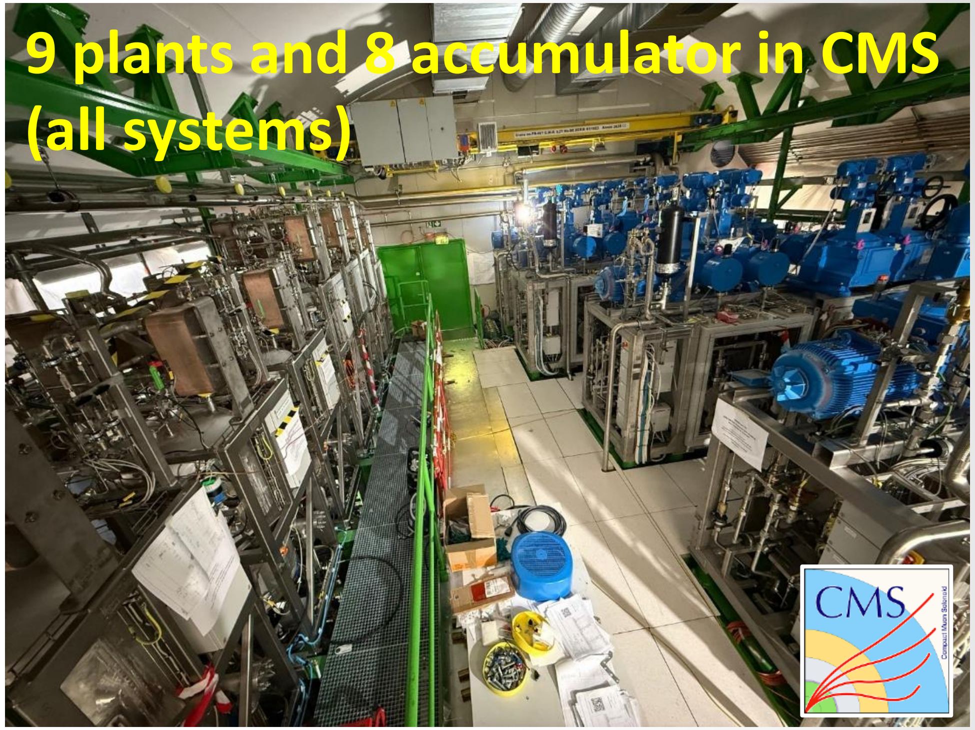
Baby-DEMO test system
2017-



R744 system A
2021-

2PACL systems for ATLAS and CMS Phase 2 upgrade



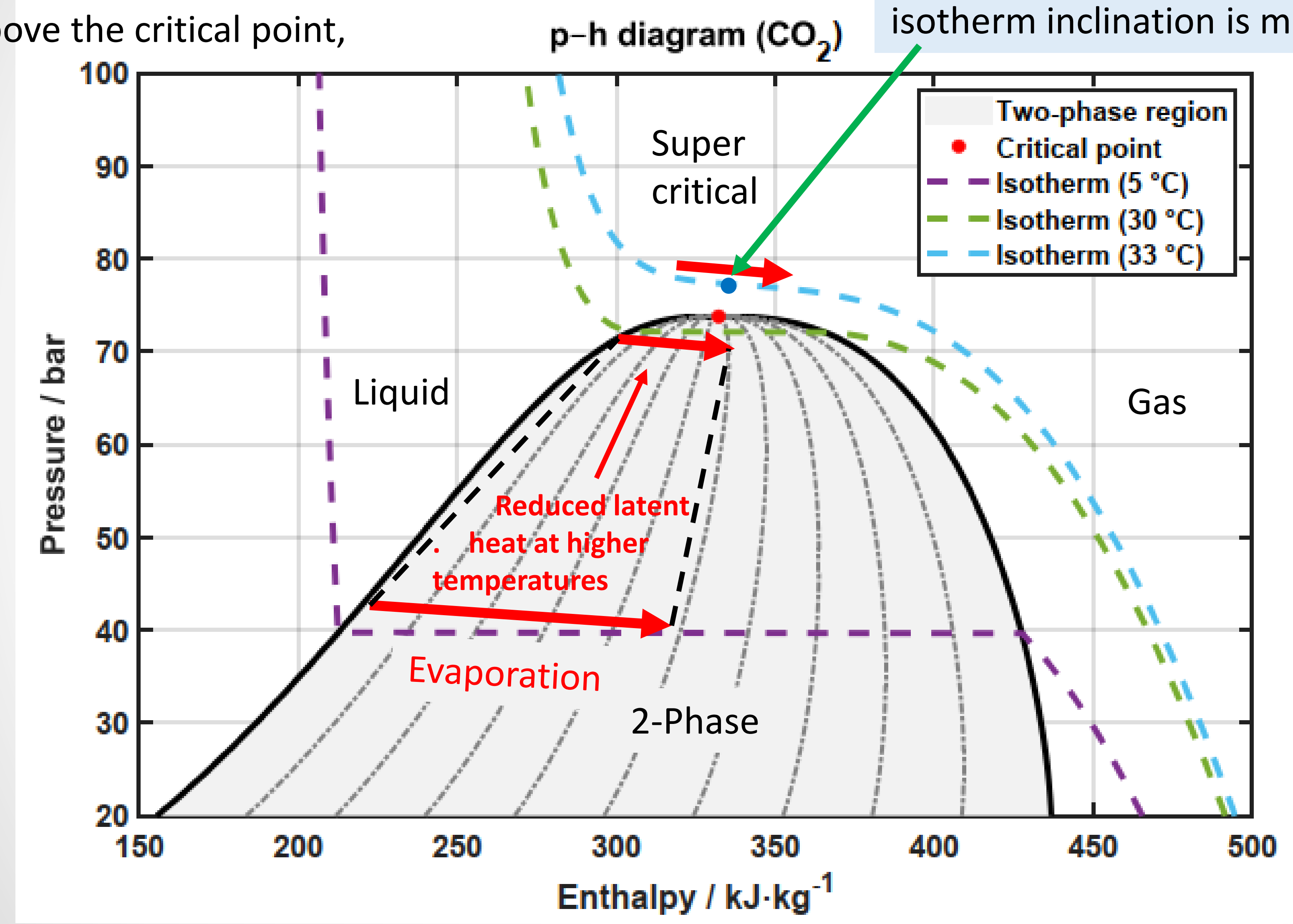


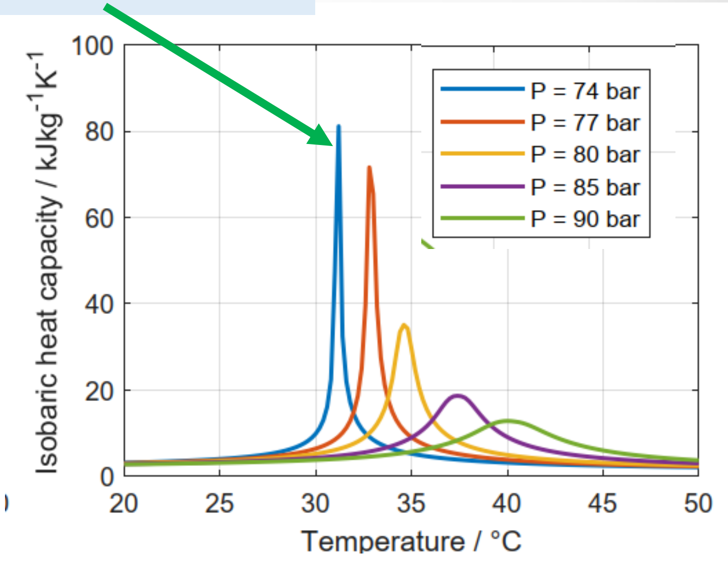
- 1 system installed in ATLAS
  - Commissioning started, very good 1st results
- All systems installed in CMS
  - Lessons from ATLAS will be applied
  - Commissioning has started in January
  - 1st full system start up next week

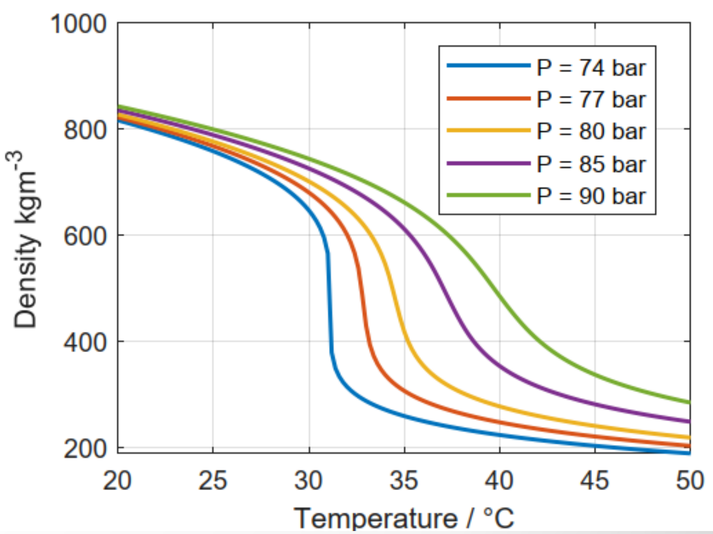
Super critical cooling vs. sub critical cooling

Close above the critical point,

Psuedo critical point (Where the isotherm inclination is most horizontal)



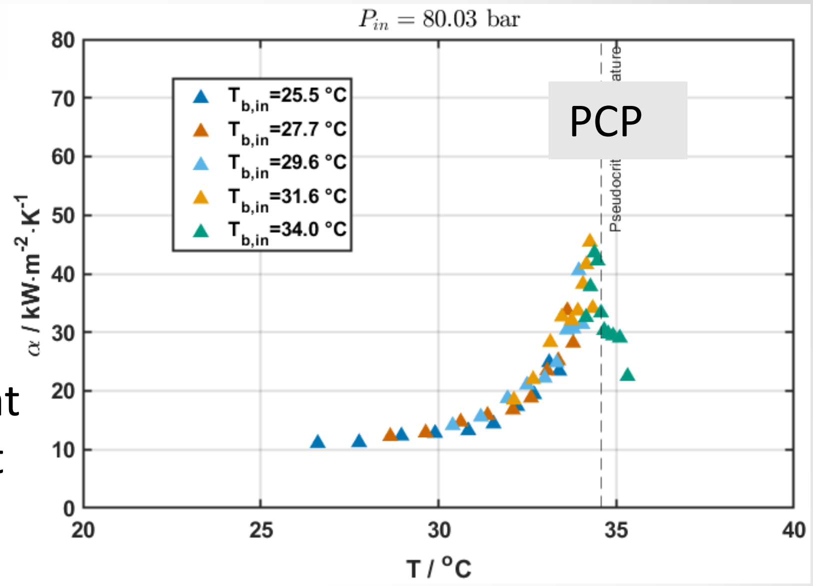




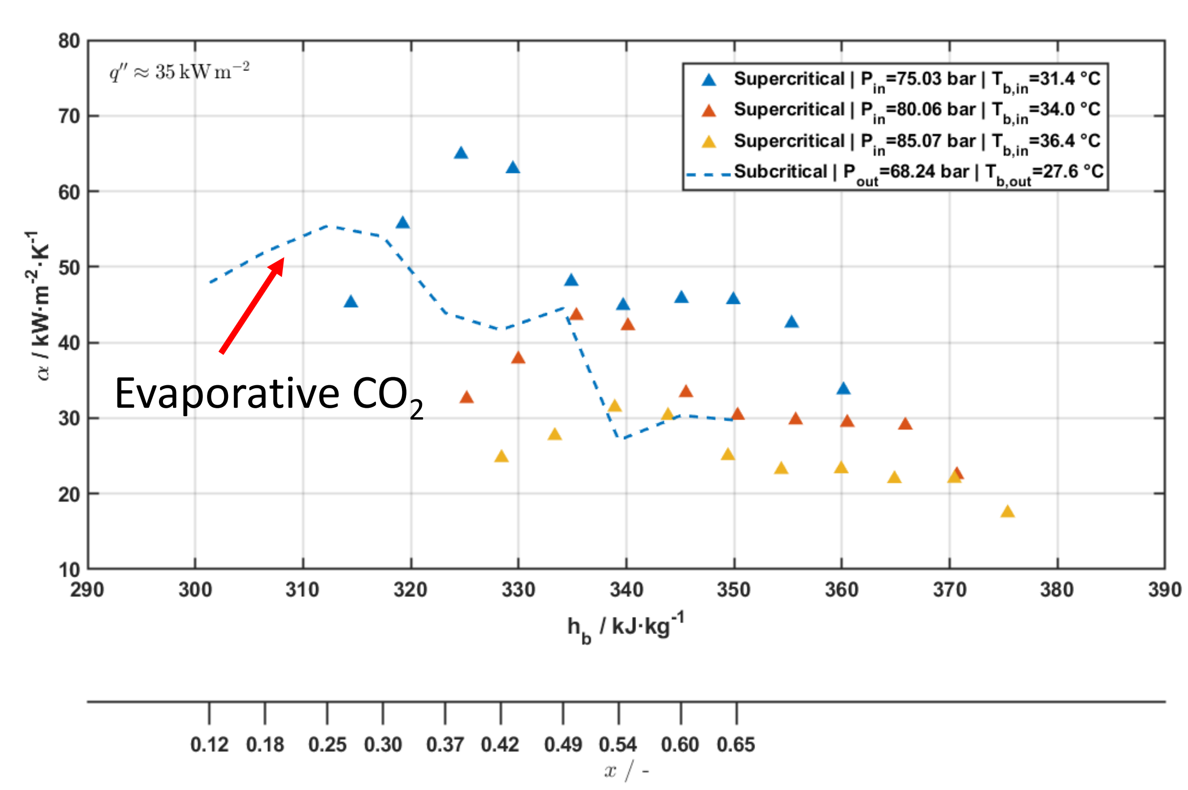
CO_2 sub critical heat transfer vs. super critical heat transfer

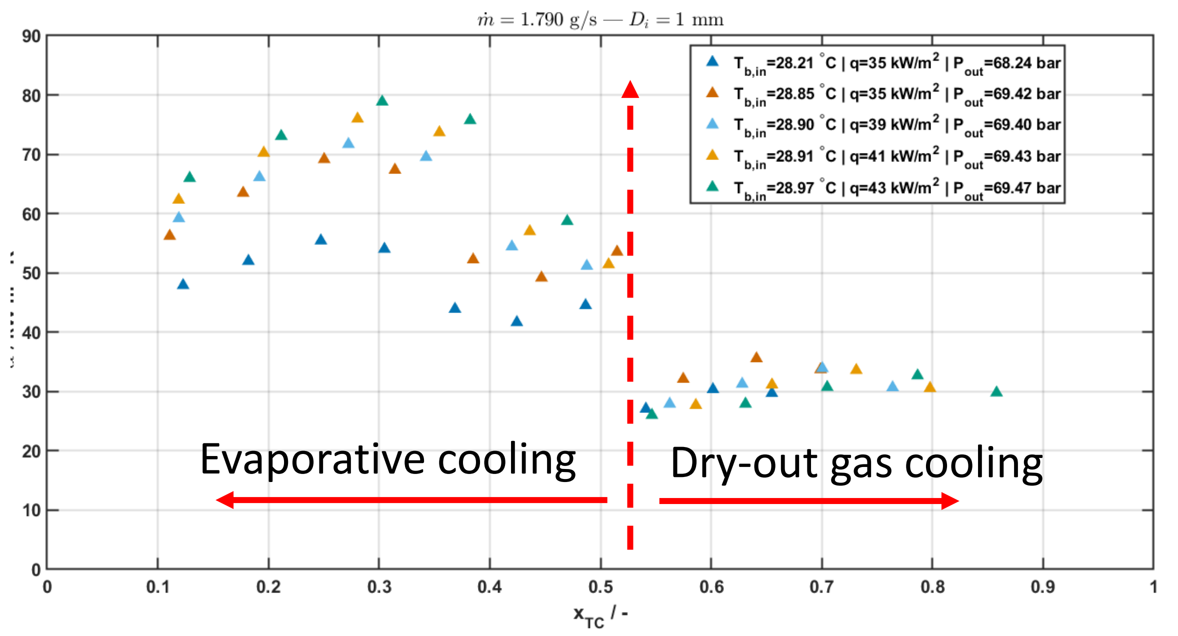
Results by Camila Pedano

Heat transfer peaks at pseudo critical point



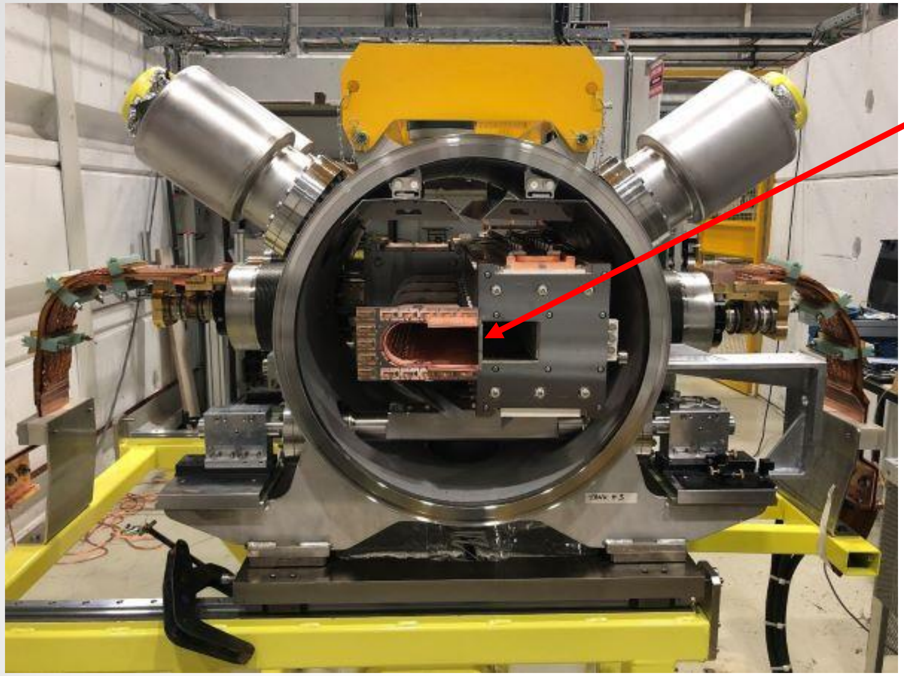
Sub critical and super critical cooling heat transfer



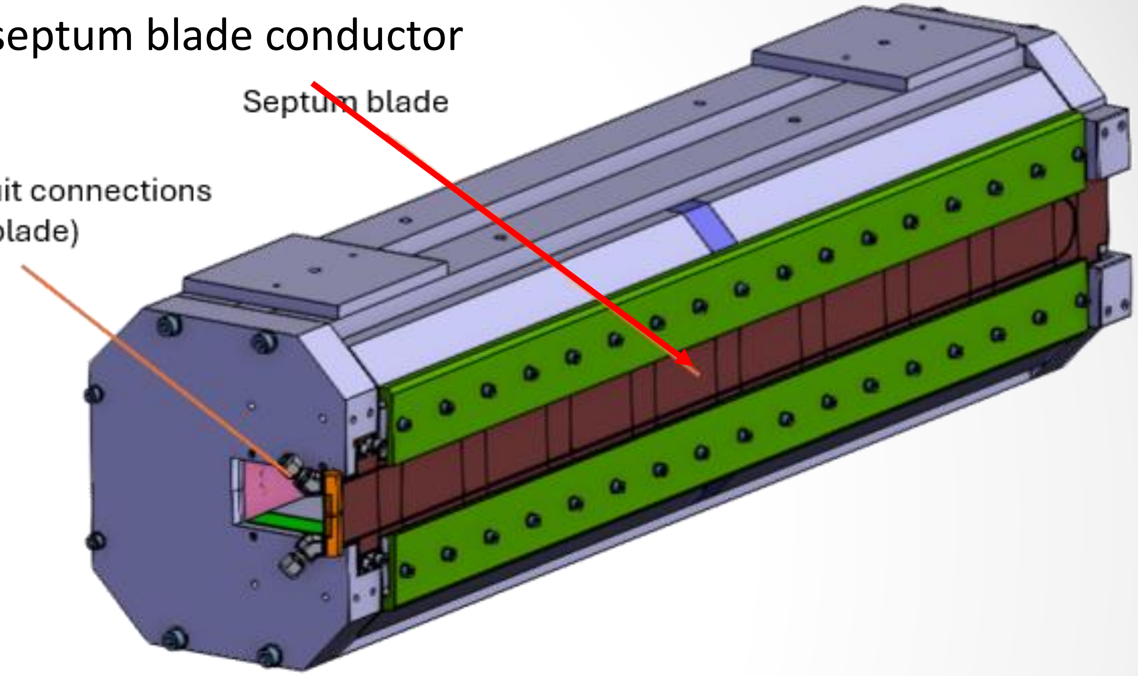


Sub critical Heat transfer at different heat fluxes

Warm Septa magnet cooling



Very thin septum blade conductor



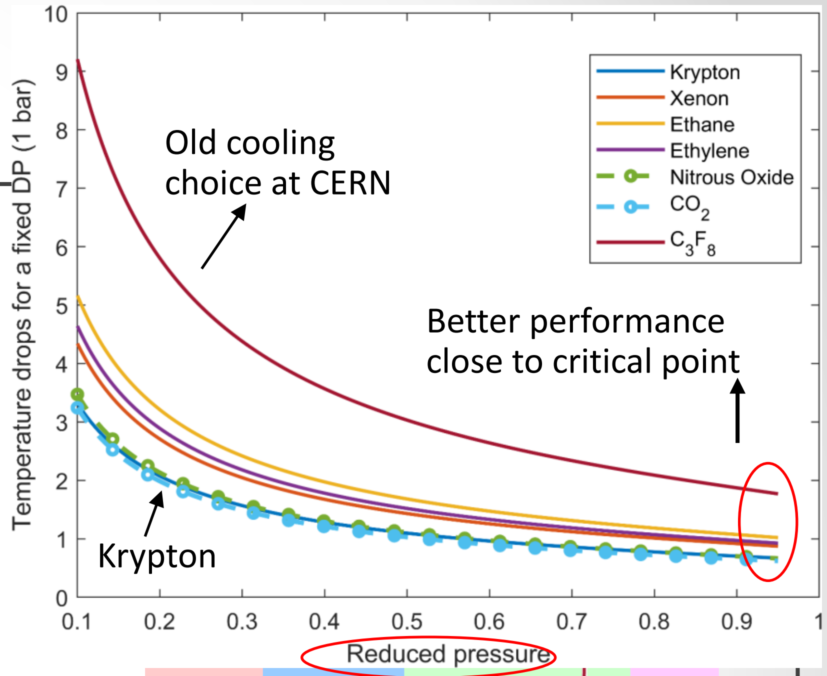
- We are currently looking into the application of replacing water with CO_2 in the HMS40 septa magnet (SY-ABT Group)
- 1st estimations show a flow decrease of 90% (97% pressure drop reduction), reducing the high speed (erosion) to comfortable numbers
  - Current magnets 6-15 m/s!
- With CO_2 not being on the limit, more conductor shrinking seems feasible

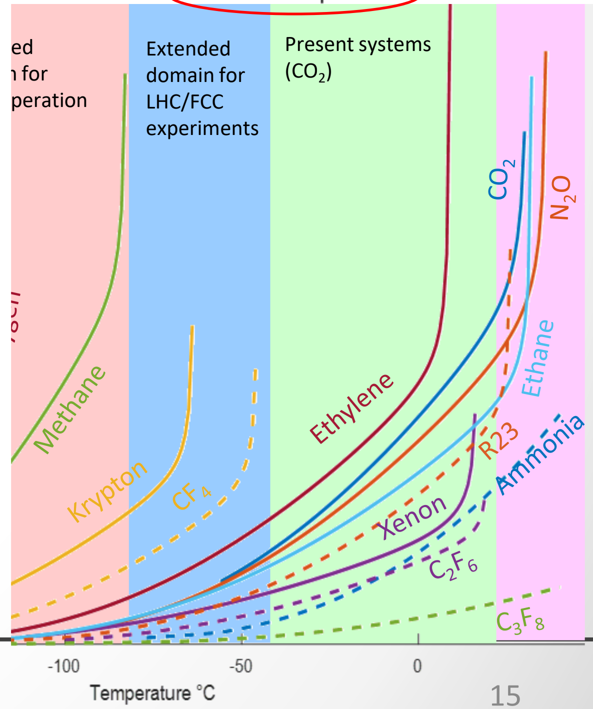
Super critical vs sub critical summary

- Super critical CO_2 gives very good cooling performance above 32°C
- Below 30°C evaporative CO_2 works well, and can rely on the past 25 years of development experience
- Super critical CO_2 has similar performance wrt evaporative but is a single phase fluid, this might give advantages in flow distribution.
- EP-DT-DC continuous research within the DRD8 collaboration to explore the sCO2 behavior.
- The system for a sCO_2 system is rather similar to the known 2PACL and can be one system operating in both regimes
- CO_2 is a very good replacement for water
  - When water is over the limit (Too high flows needed) than CO_2 is your solution!

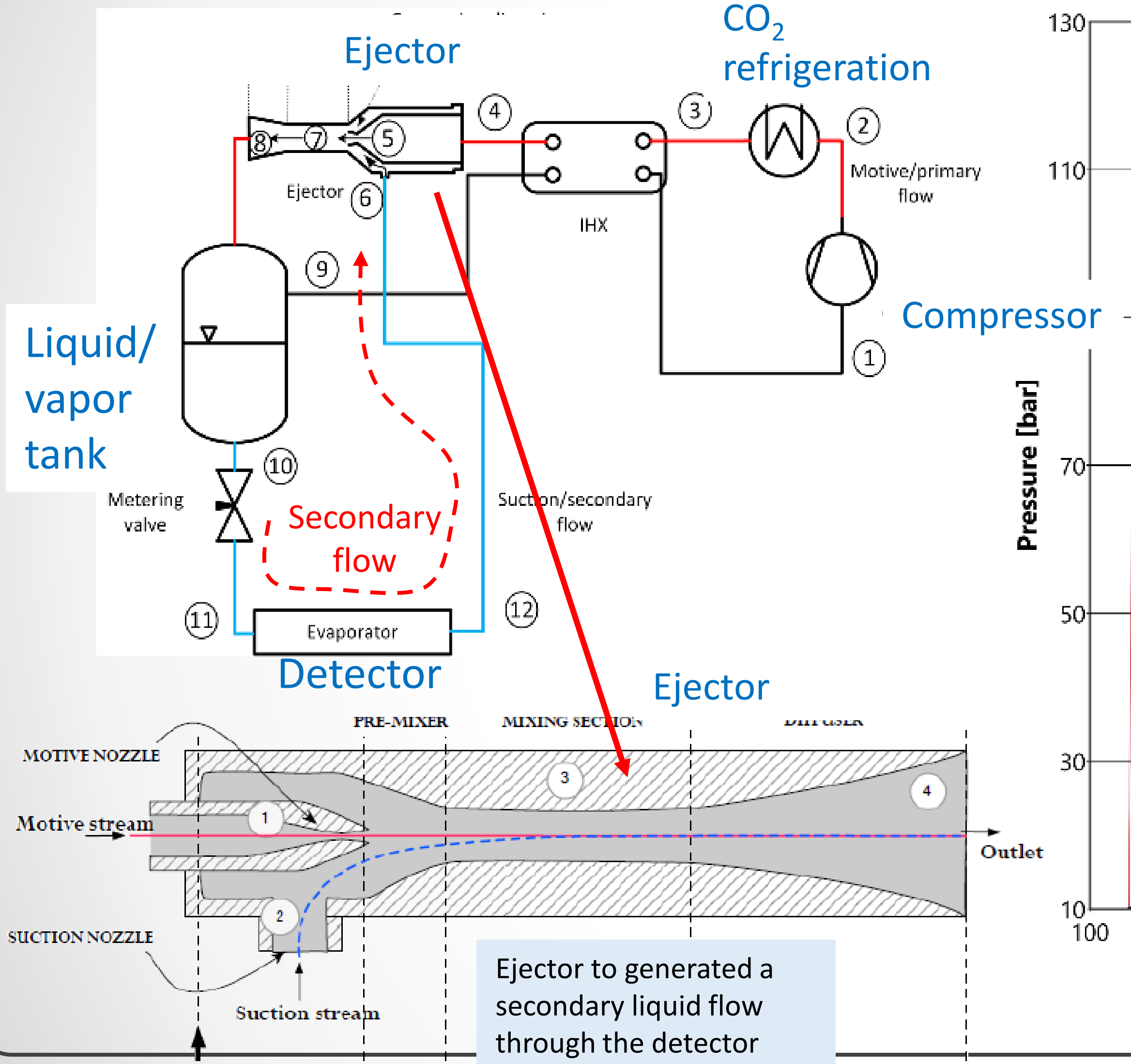
Ultra cold Krypton cooling (<-60°C)

- For the cold range below the application of CO_2, Krypton has been identified as a promising natural refrigerant.
- Application in both super critical and subcritical state.
  - Same expected advantages as sCO_2 above the critical point
  - Krypton has never been considered as a refrigerant before
  - R&D project in EP-DT-DC together with NTNU Trondheim (Norway)
- A feasibility demonstration has been performed by PhD project of Luca Contiero
  - Very promising results, looks in 1st glance comparable behavior to CO_2 at similar reduced pressures
    - Reduced pressure is the pressure relative to the critical point pressure
  - Is Krypton the CO_2 of the cold?
- Commercial interest of this system for ultra low temperature freezing below -80°C

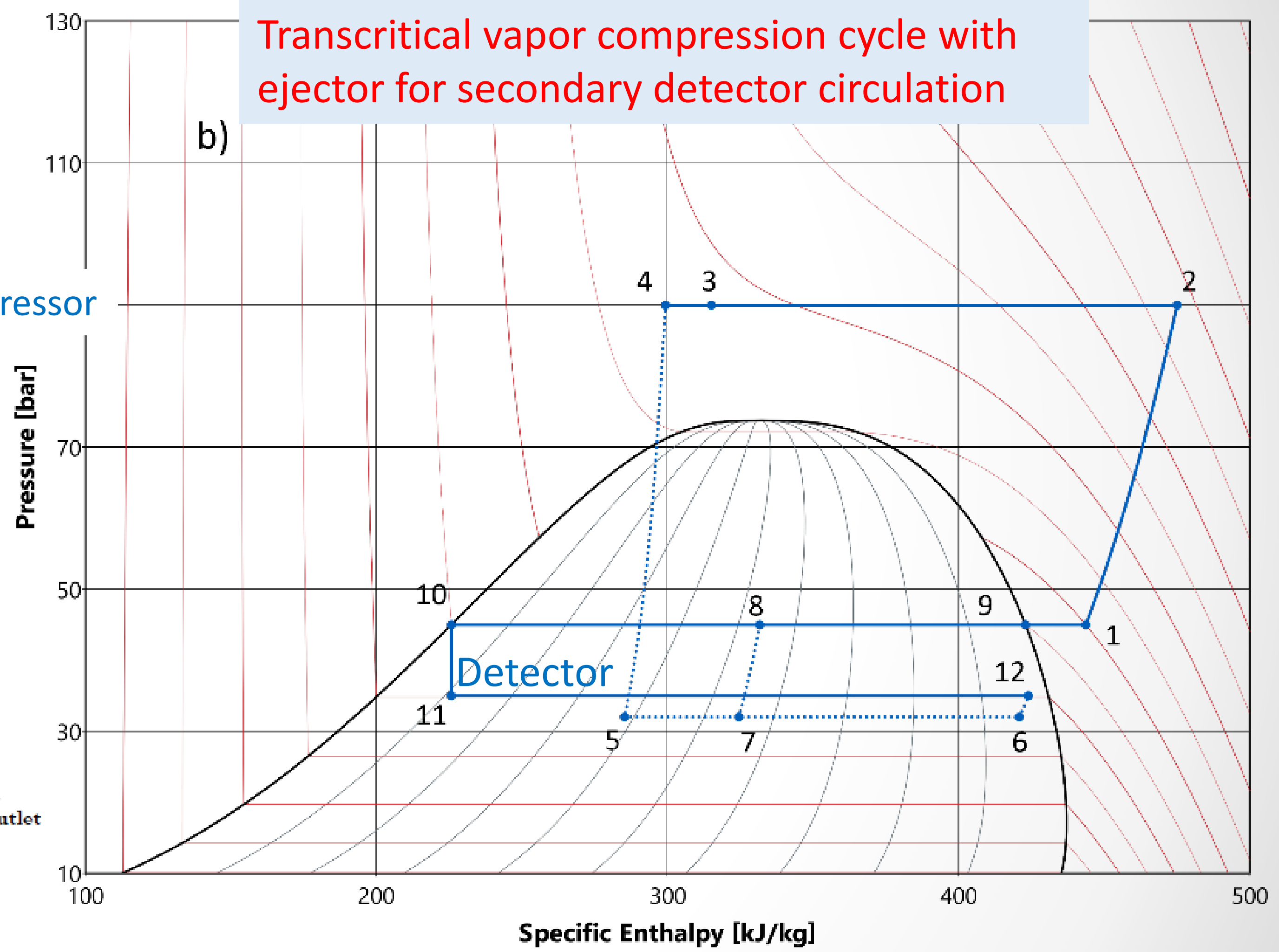




New Krypton cooling cycle with CO_2 primary cooling

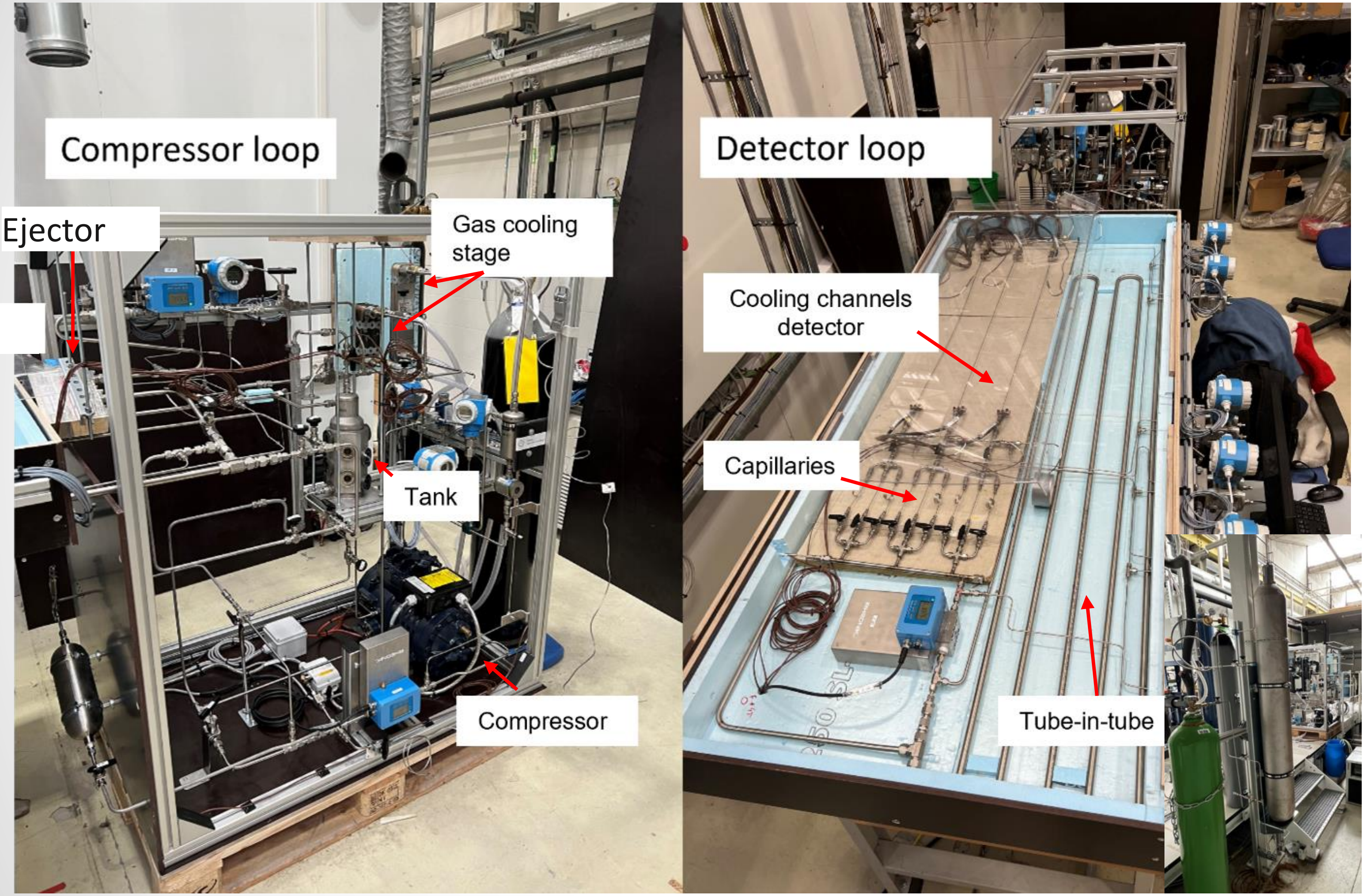


Ejector to generated a secondary liquid flow through the detector



PhD project of Luca Contiero (CERN/NTNU)

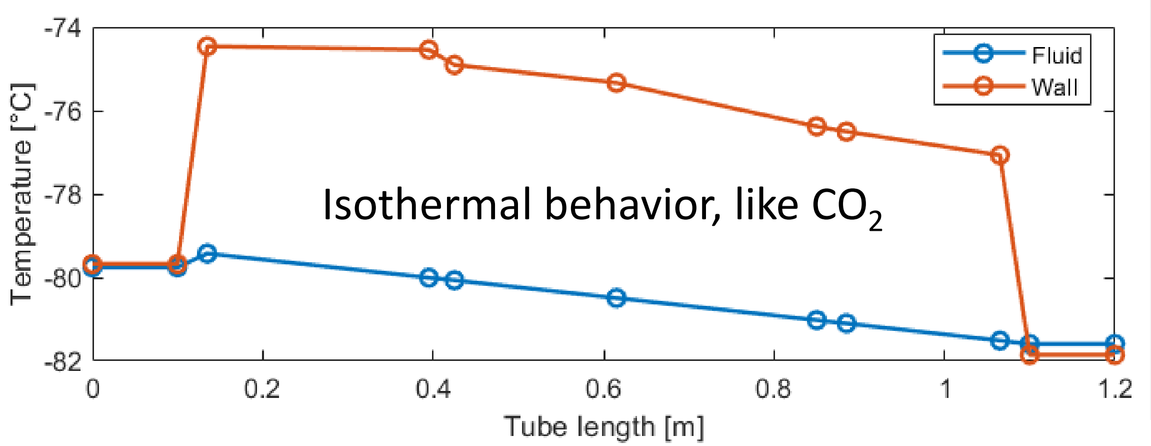
Experimental Krypton prototype

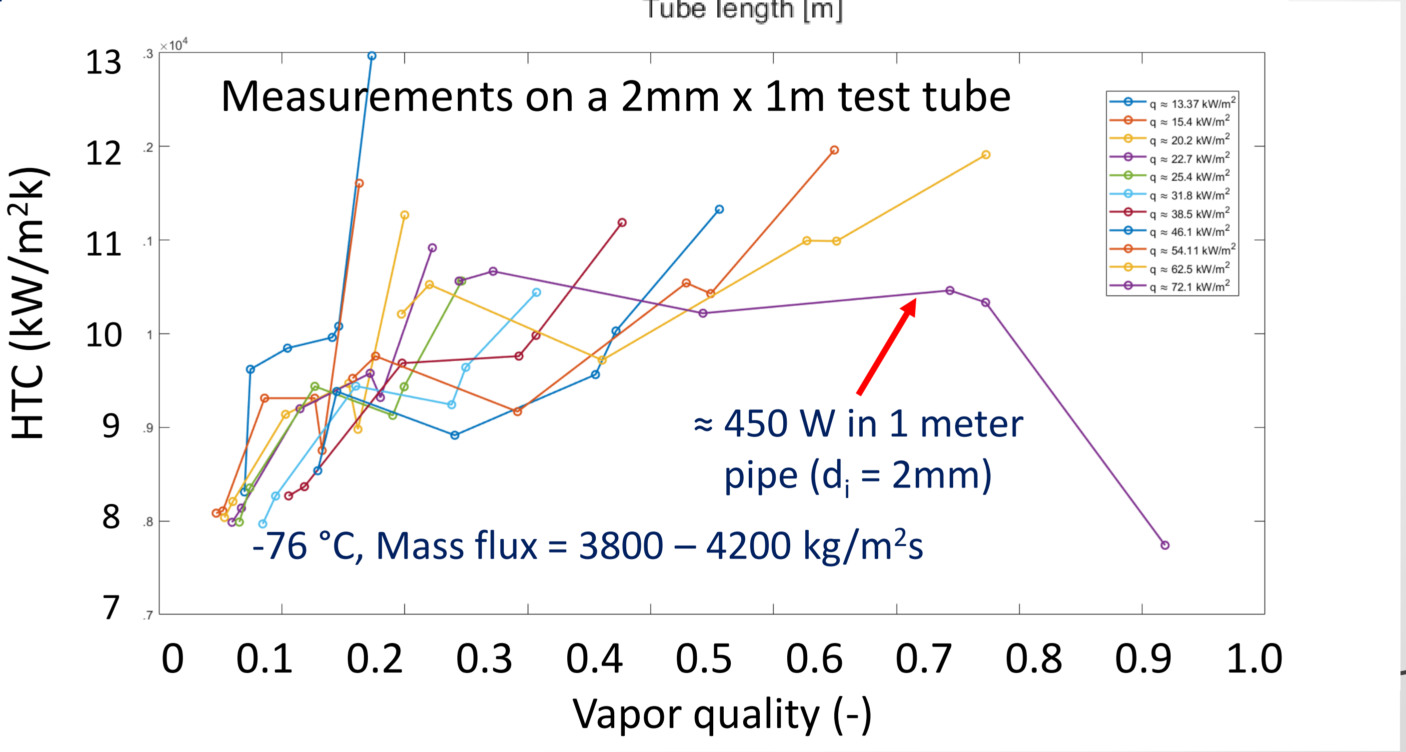


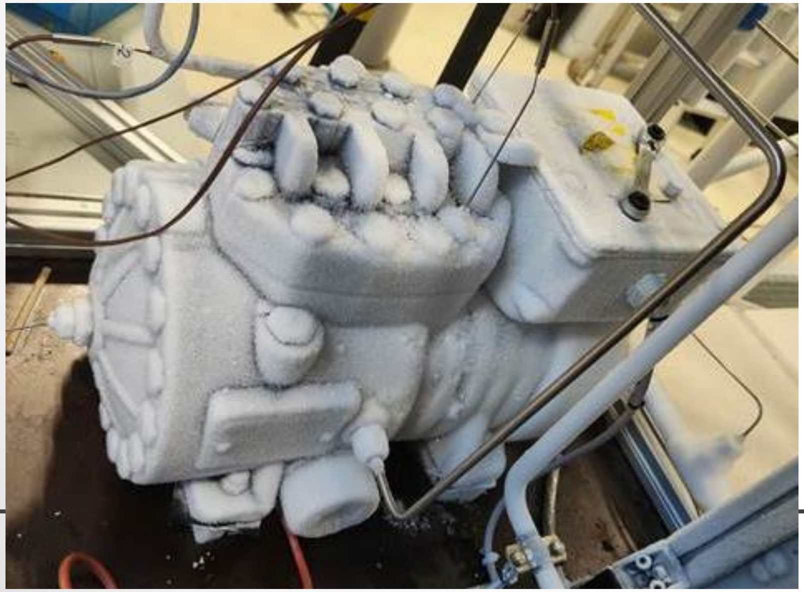
- Compressor and detector mockup box built at NTNU (Norway)
- Use of an oil-lubricated transcritical CO_2 compressor with standard oil PAG68
- Connected to the CERN R744 system
- Connected to a bladder accumulator for charge control
- Typical detector tubes for cooling demonstration

Krypton test results

- Cycle worked as designed, concept of systems demonstrated!
- Compressor was able to displace krypton gas also under very high pressures (≈ 53 bar) and densities (up to ≈ 580 kg/m^3) at the suction
- Heat transfer looks promising, reduced effects due to oil have been seen
- Pressure and temperature drops behaviour very good
- We are working on an oil free set-up to do Krypt heat transfer measurements







Summary of the cooling solutions

- Cooling between 25°C and -40°C => standard CO_2 2PACL system
- Cooling between -60°C and -140°C => Krypton cooling with compressor/ejector cycle
- Cooling between -40°C and -55°C => CO_2 with the Krypton developed compressor/ejector cycle
- Warm cooling but single phase is preferred for flow distribution: Super Critical CO_2 cooling @ 32-40°C
- Are you using water but are you at the limit? => CO_2 cooling reduces flow by an order of magnitude
- CERN EP-DT-DC is there to help…